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The GUINEVERE project at the VENUS facility

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Abstract

The GUINEVERE project is an international project in the framework of IP-EUROTRANS, the FP6 program which aims at addressing the main issues for ADS development in the framework of partitioning and transmutation for nuclear waste volume and radiotoxicity reduction. The GUINEVERE project is carried out in the context of domain 2 of IP-EUROTRANS, ECATS, devoted to specific experiments for the coupling of an accelerator, a target and a subcritical core. These experiments should provide an answer to the questions of on-line reactivity monitoring, sub-criticality determination and operational procedures (loading, start-up, shut-down, ...) in an ADS by 2009-2010. The project has the objective to couple a fast lead core, within the VENUS building operated by the SCK•CEN, with a neutron generator able to work in three different modes: pulsed, continuous and continuous with beam interruptions at the millisecond scale. In order to achieve this goal, the VENUS facility has to be adapted and a modified GENEPI-3C accelerator has to be designed and constructed. The paper describes the main modifications to the reactor core and facility and to the accelerator, which will be executed during the years 2008 and 2009, and the experimental programme which will start in 2009.

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1. Introduction

The GUINEVERE project is an international project in the framework of FP6 IP-EUROTRANS (FI6W-CT-2005-516520). The IP-EUROTRANS project aims at addressing the main issues for ADS development in the framework of partitioning and transmutation for nuclear waste volume and radiotoxicity reduction. The GUINEVERE project is carried out in the context of domain 2 of IP-EUROTRANS, ECATS, devoted to specific experiments for the coupling of an accelerator, a target and a subcritical core. For this purpose, there is a need for a lead fast critical facility connected to a continuous beam accelerator.

Since such a programme/installation is not present at the European nor at the international level, SCK•CEN and CNRS have proposed to use a modified VENUS critical facility located at its Mol-site and to couple it to a modified GENEPI accelerator working in current mode: the GUINEVERE project (**G**enerator of **U**ninterrupted **I**ntense **NE**utrons at the lead **VE**nus **RE**actor). During 2008 and 2009, the VENUS facility will be modified in order to allow the experimental programme to start in 2009. These experiments should provide an answer to the questions of on-line reactivity monitoring, sub-criticality determination and operational procedures in an ADS by 2009-2010.

2. Modifications to the VENUS facility

The VENUS reactor was built in 1963-1964 and is a water moderated reactor ("zero-power critical facility"). The VENUS reactor is made critical by increasing the water level in the reactor. In case of an emergency stop, the water can be evacuated in a very short time by opening safety valves to so-called dump tanks.

The execution of the GUINEVERE project will involve two major modifications at the SCK•CEN site: first of all, the modifications which are connected to the installation of the new GENEPI-3C accelerator at the VENUS critical facility and its coupling to the core; secondly, the adaptation of the VENUS critical facility to host a fast lead core, further on referred to as VENUS-F.

After consultation with the European partners, it was concluded that a vertical beam-line penetration in the core would represent a significant added value to the project. To implement the vertical penetration option, the accelerator has to be put in a technical room to be constructed on top of the VENUS bunker (see Fig.1).

To change the water-moderated thermal reactor into a fast lead reactor, two main modifications are necessary:

- Installation of a shut-down system based on shut-down rods suspended by electro-magnets.
- Construction of fuel assemblies with lead blocks and uranium fuel for the core and large lead blocks for the reflector.

For the shut-down system, we have chosen to use the standard philosophy of safety rods which fall in the core under the influence of gravity upon receiving the signal for de-energizing of the electro-magnets. The safety rods consist of an absorbing element with a fuel follower. In case a safety rod is up, its fuel follower is at the height of the core thereby eliminating core perturbation. In this way, an antireactivity is inserted in case of a rod drop due to removal of fuel and replacement by absorber material.

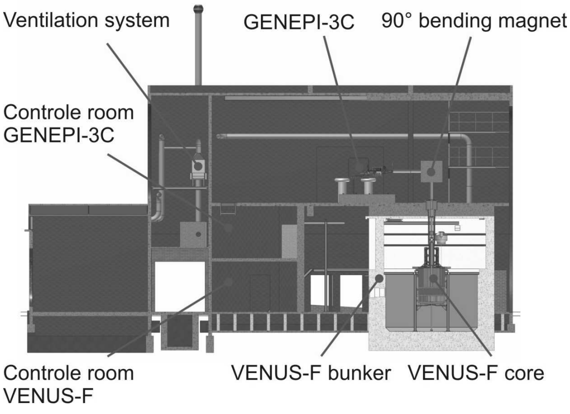

Figure 1: Side view of the modified VENUS facility

3. The new GENEPI accelerator design

The GENEPI-1 (**GE**nérateur de **NE**utrons **P**ulsé **I**ntense) accelerator was designed and built by CNRS Grenoble to enable neutronic experiments in the MASURCA reactor at CEA Cadarache in the framework of FP5 MUSE. This programme investigated reactor kinetics measurement techniques aiming at sub-criticality determination in order to provide recommendations for the operation of a nuclear reactor coupled with an accelerator. Most of the measurements required a pulsed neutron source with very short pulse duration (< 1 μs), short leading and lagging fronts (100 ns) and a high intensity (ion peak current ~ 40 mA). To reach these objectives a 250 kV accelerator coupled to a pulsed deuteron source and followed by a transport line bringing the beam onto a deuterium or tritium target was built, in this way producing a pulsed neutron source through $D(d,n)^3He$ or $T(d,n)^4He$ reactions.

Based on the GENEPI-1-2 experience (a copy of the GENEPI-1 accelerator "GENEPI-2" is operated at the PEREN facility, LPSC Grenoble), a GENEPI-3C accelerator with new specifications is developed by the French CNRS/IN2P3 teams for the experimental programme GUINEVERE. It will operate in the pulsed mode with the same characteristics as the GENEPI-1-2 machines to perform dynamic reactivity measurements in the new VENUS-F core configurations. To validate the reactivity monitoring methodology, the operation in the continuous mode, as for a power ADS, is also required. The current to power relationship will be investigated, and the techniques experimented with the pulsed source will have to be validated in the conditions of a brief interruption of the continuous beam. The specifications in this new mode are given in Table 1.

Table 1
Specifications of GENEPI-3C in DC mode.

Mean current	160 μA to 1 mA
Beam trip rate	0.1 to 100 Hz
Beam trip duration	~20 μs to 10 ms
Transition time (on/off)	1 μs
Beam spot size	20 to 40 mm in diameter
Max. neutron production	5×10^{10} n/s
Reproducibility	1% from pulse to pulse

In this new facility the beam will penetrate the VENUS core vertically for core symmetry reasons and subsequent calculation and interpretation simplification. For core assembly operations and GENEPI-3C target changes, the vertical beam line must be entirely removed from the reactor. This induces a special design of the vertical line of GENEPI-3C which will be embedded in a supporting structure that can be hoisted along guiding structures by means of a crane and lifted above the reactor to the accelerator level. The general layout of the machine is shown in Fig.2.

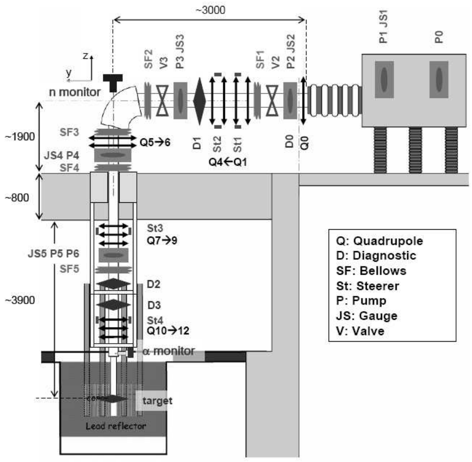

Figure 2: Layout of the GENEPI-3C structure.

The ion source sits in the high voltage head lying above the reactor bunker, followed by a horizontal beam transport section of 3 m at the exit of the accelerator tube. Beam transport is ensured with electrostatic quadrupoles. A first group of 4 quadrupoles transports and focuses the beam at the 90° dipole magnet which deflects the beam downwards. A quadrupole doublet is located at the exit of the magnet and no optical element is foreseen in the thickness of the bunker ceiling. Two quadrupole triplets located on the vertical beam line above the reactor core focus the beam onto target. It is located at the end of a short optic free thimble inserted into the reactor core.

One of the main challenges of the GENEPI-3C machine is to operate the duoplasmatron ion source, particularly well suited for pulsed mode operation, in continuous mode and with short and repetitive beam interruptions. To do so the continuous operation of the ion source was investigated on a test bench purpose-built for the GUINEVERE program at LPSC. The source was operated up to 3 mA total direct deuteron DC current without major difficulty. Preliminary tests also seem to indicate the possibility to turn off an established DC beam with a transition time on the order of 1 μs. The fraction of the beam efficient for neutron production on the target is the D^+ atomic ions bent by the 90° magnet. Work is in progress to optimize their production i.e. to minimize the D_2^+ and D_3^+ ion fractions removed by the dipole.

4. Design of the GUINEVERE core

4.1. *Choice of the fuel lattice*

First investigations on the GUINEVERE core design were based on the initial proposal made by the SCK•CEN mid 2006. At that moment, the basic features of the first critical core were as follows:

- The core is a fast lead one, consisting of a fuel zone surrounded by a lead radial reflector, arranged within the existing vessel of the VENUS facility (160 cm in diameter).
- The fuel sub-assemblies (S/A's) are composed of a fuel part surrounded by two lead axial reflectors.
- The fissile material is 30% ^{235}U enriched metallic uranium. Bars of cylindrical shape are ½ inch in diameter (1.27 cm), 8 inches in length (20.32 cm) and covered with a nickel deposit about 70 µm in thickness. They are provided by the CEA.
- At the core centre, a channel is arranged in order to allow the crossing of the neutron generator glove finger. This channel has the same cross section as one sub-assembly.

From the very beginning, various constraints and considerations also influenced and guided the design of the core:

- The limited amount of fuel (about 1200 kg).
- The search, inside the sub-assemblies (S/A), of a symmetric arrangement in order to avoid loading error issues and any orientation constraint.
- The interest to limit the reactivity worth of peripheral fuel sub-assemblies.

In addition, in order to reduce the hazards associated to experiment modelling, a core "easy" to simulate was looked for. Hence, the search of configurations and lay-outs as homogeneous, symmetrical and cylindrical as possible constituted an important objective.

From these initial specifications, basic fuel lattices were investigated (see Fig.3) with a regular mixture of lead bars and metallic uranium rodlets, with the goal to obtain a core as large as possible:

- A "5 x 5" pattern with 9 fuel stacks and 16 lead stacks.
- A "7 x 7" pattern (16 fuel stacks, 33 with lead).
- A "5 x 5 with lead plates" pattern (9 fuel stacks vs. 16 lead stacks) allowing to get a lower fuel content and to preserve the regularity of the design.

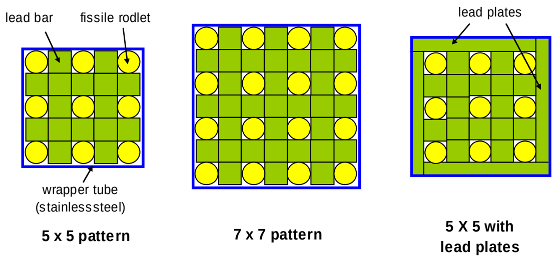

Figure 3: Cross-section of various patterns studied.

The "5 x 5" and "7 x 7" lattices were rejected for two main reasons : 1) they lead to limited core sizes, 2) the reactivity worth's of the peripheral sub-assemblies are too important (> 0.5 $). Further discussions and work on the "5 x 5 with lead plates" solution lead to add an internal steel casing and to distribute sheathed and bare lead bars following a specific arrangement (see Fig.4).

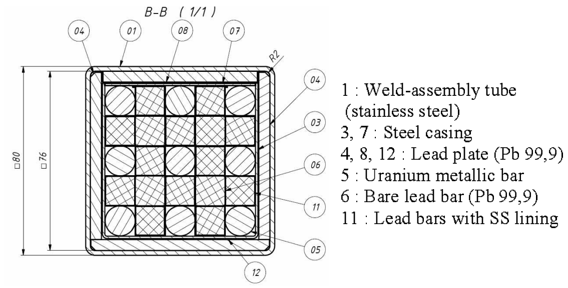

Figure 4: Cross-section of a fuel sub-assembly in the fuel part – Final design.

4.2. *Set-up of the central channel and absorber rods*

During the first phase of this design and in the line of the core configurations loaded in the MASURCA facility during the MUSE-4 experiment series, the presence of a lead buffer surrounding the neutron source was considered. Although the study demonstrated that a thickness of more than 25 cm was necessary to slow down 95% of the neutrons provided by the generator, the principle to set-up such a device was nevertheless kept in order to let some space free for the crossing of the neutron generator thimble (at this moment, it seemed that a channel of 9-10 cm, greater than the dimension of one sub-assembly, was necessary).

Two solutions were so envisaged: 1) a large zone corresponding to the volume of nine central sub-assemblies, 2) a smaller one obtained by removing only four sub-assemblies. In both cases, calculations showed that it would be difficult to reach the criticality. Using, as a complement, sub-assemblies with a higher fuel content (with 13 fuel stacks), solutions seemed possible but none really satisfying. As a result, the new strategy proposed was the following one: a “clean” critical core is initially built (a core without buffer and central hole) to assess the reactivity scale by the multiplication method through the entire program, in a second step the four central sub-assemblies are removed to set-up the lead buffer and the beam tube.

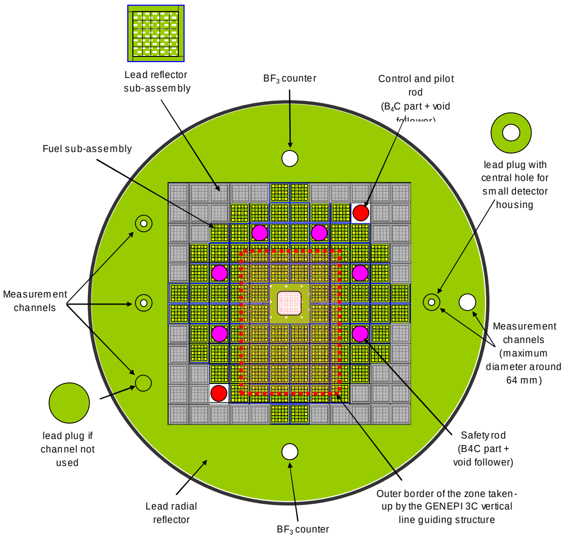

Figure 5: Principle scheme op core configurations.

After the main features of the fuel sub-assemblies and the central zone in view of hosting the neutron source were fixed, we addressed the key issue of the neutronic control of the core. Firstly, we supposed the absorbers rods would be made of a natural boron carbide block, 7 cm in diameter and 60.96 cm long. When the rods are up, the bottom of the B_4C part is located at the top of the fuel zone. When the rods are down, the absorber parts are in front of the fuel zone. Secondly, we considered a maximum of eight absorber rods to take in consideration the number of control rod mechanisms currently available at the VENUS facility.

Positioning all the absorber sub-assemblies at the fuel/reflector interface, the reactivity worth was less than 7 dollars. Putting them inside the fissile zone, the negative effect produced by the removal of the fuel part from the core and the insertion of the B_4C into the core varied from 8.5$ up to around 19$ depending on the distance from the core centre. At the end, owing to:

- the constraint imposed by the presence, above the core, of a device devoted to guide the vertical beam line,
- and the need to get both safety and control rods,

we finally converged on the absorber rods distribution as it is shown in Fig.5.

4.3. *Summary of core design and main neutronic parameters*

Although the characteristics of some parts of the core are still not finalized, the evolutions that are expected should not modify in an important way the specifications that are detailed hereafter. So, to sum-up:

- The initial critical core is composed of a fuel zone radially surrounded by a lead reflector.
- The fuel sub-assemblies consists of, from the bottom to the top, a fuel part 60.96 cm long, a stainless steel (SS) block about 7 cm long and a lead part about 40 cm in length. The fuel part consists of an arrangement of 9 fissile stacks and 16 lead stacks that are put in a steel casing, itself surrounded by four lead plates. The whole, i.e. the fuel part, the SS block and the lead block, are mechanically linked and then inserted in a stainless steel wrapper tube.
- Every fuel sub-assemblies rest on a square section grid able to host 12 x 12 sub-assemblies. This grid is made of stainless steel and has the same thickness (about 7 cm) than the SS block arranged in sub-assemblies. The grid also hosts lead reflector sub-assemblies that are built following the same principle than the fuel sub-assemblies.
- Eight absorbers rods are used for the safety of the reactor: two pilot rods and six safety rods. Both use boron carbide with natural boron as absorber material. Pilot rods just consist of an absorber part that slides inside a wrapper tube. They are normally placed in the reflector part of the core at the periphery of the fuel zone. Their position is not frozen. Control rods consists of, from the bottom to the top, a fuel part (similar to the one of fuel sub-assemblies), a stainless steel block (also

similar to the one of fuel sub-assemblies) and an absorber part, about 60 cm long, loaded with natural boron carbide. Control rods take-up fixed position as it is showed in Fig.5.

- A lower lead reflector, with the same height than the upper one, is arranged under the grid that supports sub-assemblies.
- In view of the measurement programme, experimental axial channels are opened into the radial lead reflector.

From the initial critical reference configuration, sub-critical configurations will be set-up by removing the four central fuel sub-assemblies and replacing them by the lead buffer with the central channel for the GENEPI glove finger crossing. The reactivity effect associated to such a modification of the core is expected to be between 3000 pcm and 4500 pcm depending on: 1) the number of fuel sub-assemblies required for the critical core and 2) the dimension of the central channel. If necessary, the reactivity level of sub-critical configurations will be adjusted by adding fuel sub-assemblies at the periphery of the fuel zone,

Finally, the Fig.6 presents a vertical section of the critical core and Table 2 indicates the main neutronic parameters associated to the current design.

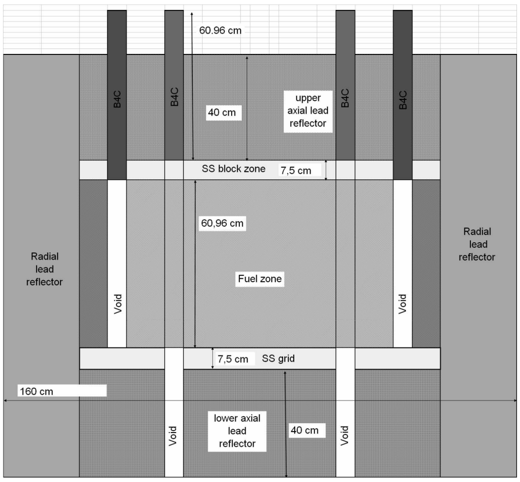

Figure 6: Vertical section of the critical core with all rods up.

Table 2
Main neutronic parameters of the critical core

Parameter	Indicative value
Fuel volumic content	17%
Spectrum hardness index	0.64
Critical mass	88 S/A's
Peripheral SA reactivity worth	200 to 250 pcm
β_{eff}	740 pcm
Λ (prompt neutron generation time)	3.8 10^{-7} s
Safety rod reactivity worth	14 $
Control/pilot rod reactivity worth	1.2 $

5. The GUINEVERE experimental programme

In the first stage of the GUINEVERE experimental programme, 2 core configurations will be studied: the SC0 critical configuration and the SC1 configuration for the nominal operation mode of an ADS.

The SC0 phase in the experimental programme will be limited to providing the necessary information for validating subcriticality measurement techniques. Radial and axial traverses will be executed and a limited number of spectral indices will be performed. Calibration of control rod worth is foreseen and rod-drop measurements will be used to determine the subcritical reactivity scale and to allow the implementation of a reference technique for validation of subcritical reactivity measurements.

The SC1 configuration will have a keff=0.97 and will be driven by the GENEPI-3C accelerator source. The characterisation of SC1 will be done by using the pulsed neutron source (PNS) area method for reactivity determination. The control rods will also be calibrated by the PNS Area method.

These control rods will be used for the current-to-flux measurements. For the static measurements, the experimental programme will consist of current-to-flux measurements with different detectors at a series of different currents. Since this type of measurement will be repeated in slightly modified configurations with different reactivity levels, a global picture about the accuracy of the current-to-flux reactivity indicator can be obtained. During the kinetic measurements, the robustness of the current-to-flux technique will be investigated under continuous variations of the beam intensity, the target state and the reactivity.

Another part of the SC1 programme consists of interim cross checking techniques at beam trips. This part of the programme requires piloting the source in continuous mode with short and prompt beam interruptions repeated several times. Two different techniques have been proposed to be used at these beam trips: fitting techniques of the prompt decaying part and the ADS source jerk technique. Both techniques will be investigated.

Finally, calibration methods will be studied. Most of the calibration methods have been investigated in MUSE. In this experimental programme we will focus on the PNS area method and noise methods with continuous beam and comparison with theory. The determination of the kinetic parameters, mean neutron generation time and delayed neutron fraction is envisaged.

In the future, two additional reactivity variants can be considered, $k_{eff}=0.95$ (SC2) and $k_{eff}\geq0.99$ (SC3). These variants of the reference configurations will be obtained by changing the peripheral region without other modifications. Apart from that, specific configurations for loading conditions (SCL) with lower k_{eff}-values in the region 0.85-0.95 will be determined based on the reference configuration. Further on, the influence of different reflector materials on the characteristics of the core and the performance of the subcriticality analysis techniques will be studied in different configurations (SCR). Finally, a XT-ADS mock-up will be studied in the SC-XT configuration.

6. Summary

In the framework of the GUINEVERE project the VENUS facility at the SCK•CEN site in Mol will be modified in order to couple a GENEPI deuteron accelerator to a sub-critical lead fast core. Modifications to the GENEPI accelerator will allow it to operate both in pulsed and continuous mode. The GUINEVERE reactor core has been designed, starting from a fast critical reference configuration consisting of fuel assemblies with lead and uranium rodlets, which will be turned into a sub-critical core by replacing four central fuel assemblies by a lead buffer with a channel for the GENEPI beamline and a tritiumtarget. The experimental programme will start in 2009 and should provide an answer to the questions of on-line reactivity monitoring, sub-criticality determination and operational procedures in an ADS system.

Acknowledgement

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